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Impact of control algorithm solutions on Modular Multilevel Converters electrical waveforms and losses

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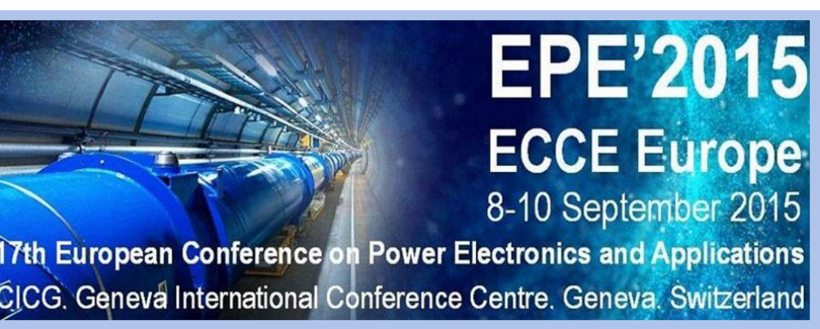
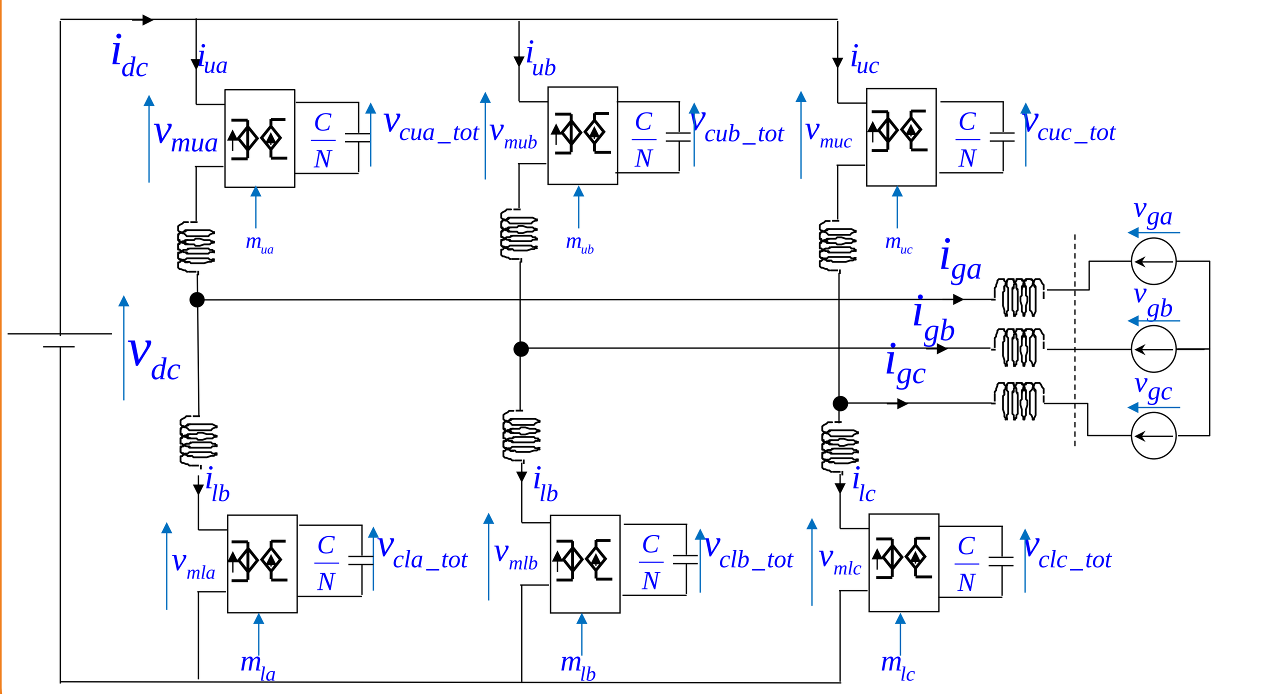


- Context : control of the stored energy of the MMC (Modular Multilevel Converter)
- Objectives :
  Study the impact of two control variants (compensation of the average or the instantaneous AC grid power) :
  differential and AC grid currents, capacitor voltages ripple, losses.

Simplified model of MMC

If capacitor voltage balancing is achieved:



Modeling of the MMC converter

$$\begin{cases} v_{ml\,i} = m_{l\,i} v_{cl\,i\_tot} \quad ; \quad v_{mu\,i} = m_{l\,i} v_{clui\_tot} \\ m_{l\,i} i_{l\,i} = \dfrac{C}{N}\dfrac{dv_{cl\,i\_tot}}{dt} \quad ; \quad m_{u\,i} i_{u\,i} = \dfrac{C}{N}\dfrac{dv_{clui\_tot}}{dt} \end{cases} \quad with \quad i \in (a,b,c)$$

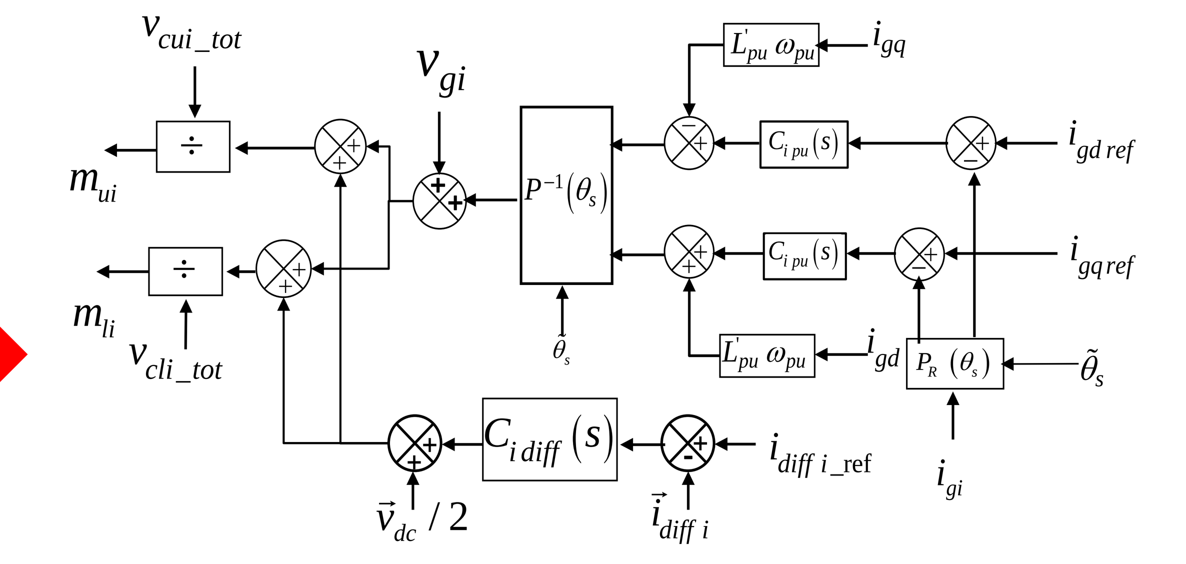
$$i_{diff\,i} = \frac{i_{ui} + i_{li}}{2} \; ; \; v_{diff\,i} = \frac{v_{mu\,i} + v_{ml\,i}}{2} \; ; \; v_{v\,i} = \frac{v_{ml\,i} - v_{mu\,i}}{2}$$

$$v_{vd} - v_{gd} = (L + \frac{L_{arm}}{2})\frac{di_{gd}}{dt} + (R + \frac{R_{arm}}{2})i_{gd} + (L + \frac{L_{arm}}{2})\,\omega\, i_{gq}$$

$$v_{vq} - v_{gq} = (L + \frac{L_{arm}}{2})\frac{di_{gq}}{dt} + (R + \frac{R_{arm}}{2})i_{v-q} - (L + \frac{L_{arm}}{2})\,\omega\, i_{gd}$$

This converter has 11 independent state variables
→Requires 11 control loops to achieve the global control

Current Control of the MMC Converter

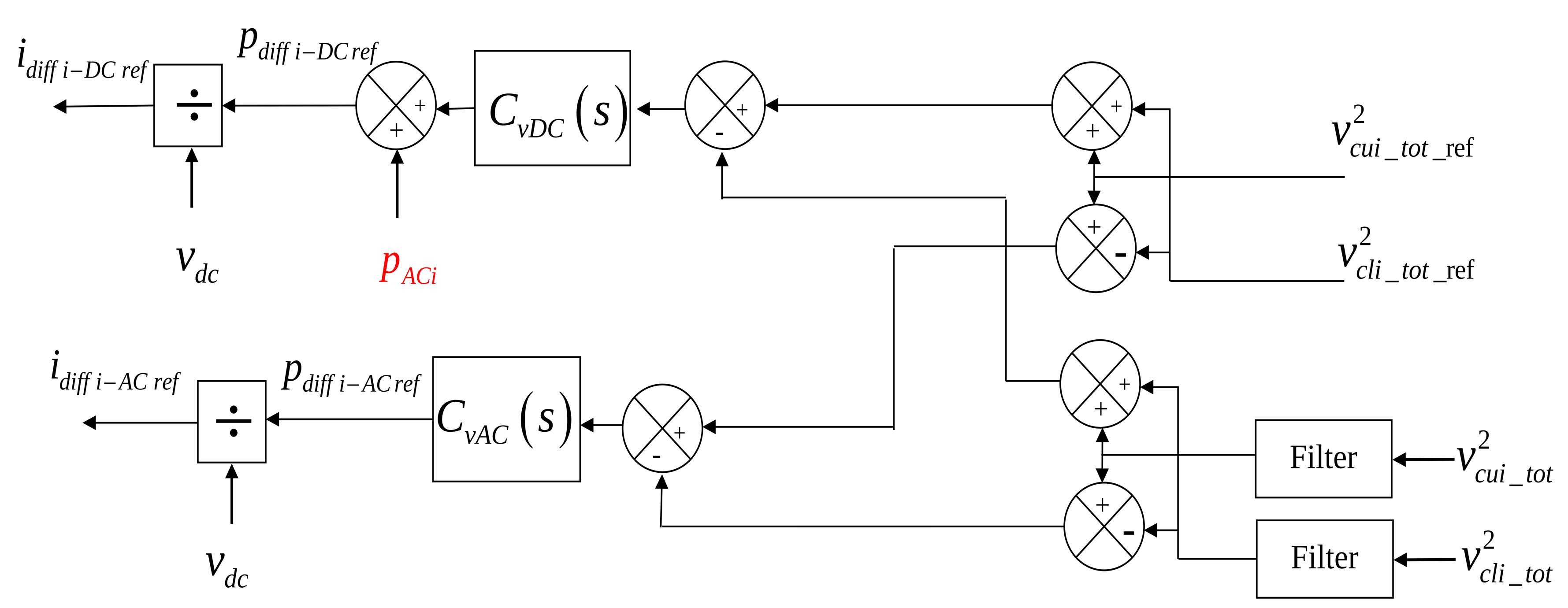


$with \quad i \in (a,b,c)$

Current control → 5 control loops

Stored Energy Control of the MMC Converter

$$\begin{cases} \left\langle \dfrac{d(W_{cli} + W_{cui})}{dt} \right\rangle_T = V_{dc}.i_{diff\,i-DC} - p_{AC\_i} \\ \left\langle \dfrac{d(W_{cli} - W_{cui})}{dt} \right\rangle_T = \hat{v}_{vi}\hat{i}_{diff\,i-AC} \end{cases} \quad with \quad i \in (a,b,c)$$



Stored Energy Control → 6 other control loops (3*sum+3*difference)

Usual assumption:

To Limit the losses, the I_{diff-i} value is limited by considering only the average power of the AC grid (P_{ac}) in the stored energy control ($p_{AC} \neq p_{DC}$)

$$p_{ACi} = \frac{P_{AC}}{3} \quad with \quad i \in (a,b,c)$$

→ introducing the AC fluctuating power term

$$p_{ACi} = \frac{P_{AC}}{3} + V_{gi} I_{gi} \cos(2\omega t + \varphi) \quad with \quad i \in (a,b,c)$$

-Reduce the ripples in the v_{c_tot} since $p_{AC} = p_{DC}$

The choice of introducing or not the fluctuating part of the AC power modifies the control →
- different quantity of activated sub-modules
- current passes through a different number of IGBT and diodes.

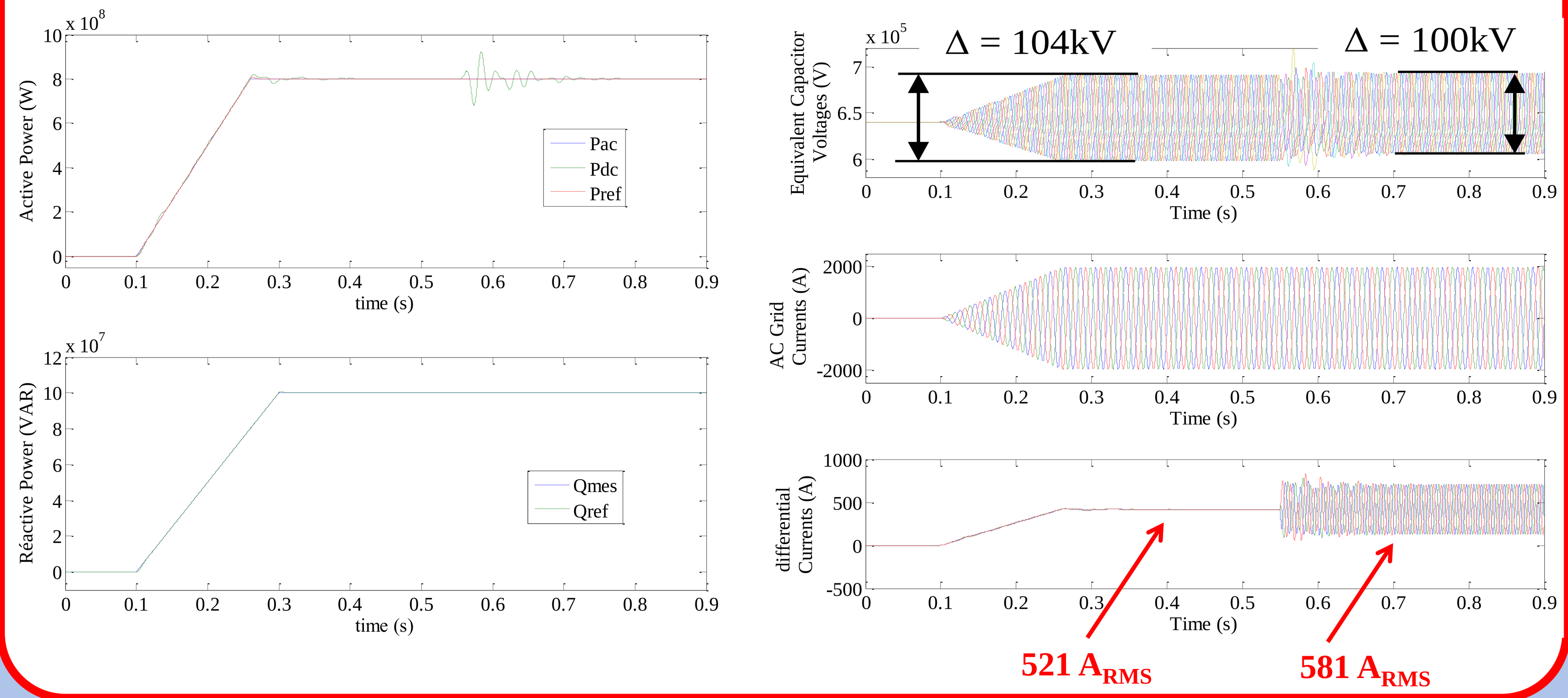
it may have sense to use a control inducing a slightly larger current if this current passes through more diodes.
- IGBT conduction losses>diode conduction losses

the hypothesis of limiting the RMS current can be questionable.

Simulation Results

L	50 mH	C	10 mF
R	50 mΩ	N	400
L_{arm}	50 mH	V_{dc}	640 kV
R_{arm}	50 mΩ	ω	314 rad.s^{-1}
S_N	1100MVA	Vg	192 kV
$Tr_{\_igdq}$	5ms	$Tr_{\,\sum Vci\_tot}$	50ms
$Tr_{\_idiffi}$	10ms	$Tr_{\,\Delta Vci\_tot}$	100ms

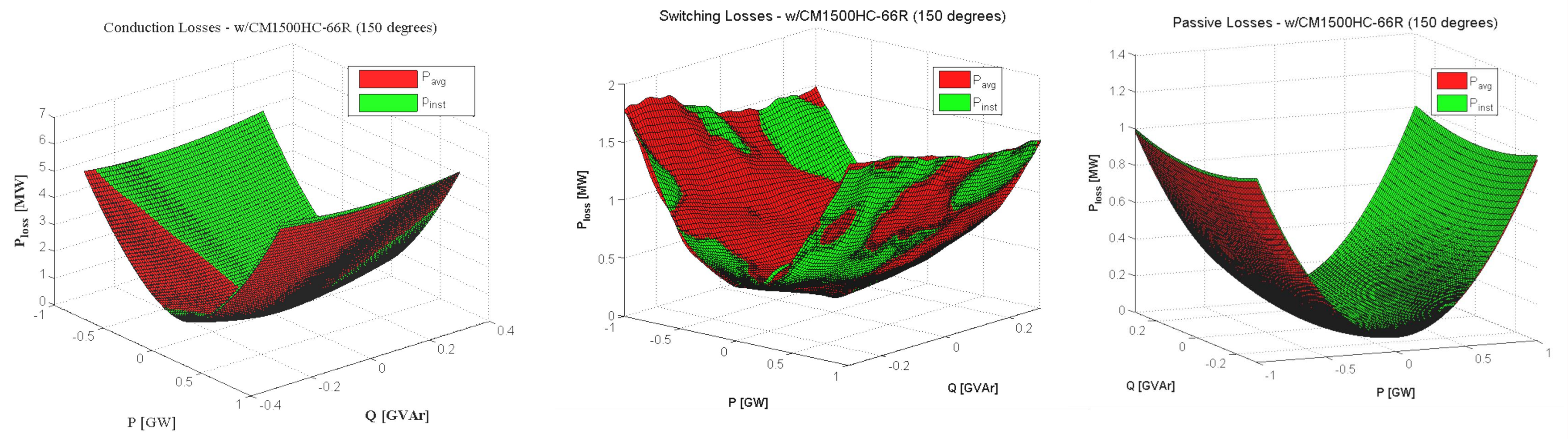
At t=0.1s : a slope is done in the AC power references (Pac) equal to 0.8 GW and the reactive reference (Qac) to 100MVAR.
Before 0.55s, the Stored Energy control compensate the average power (Pac/3)
After 0.55s, the Stored Energy control compensate the instantaneous one for each phase (p_{aci}).



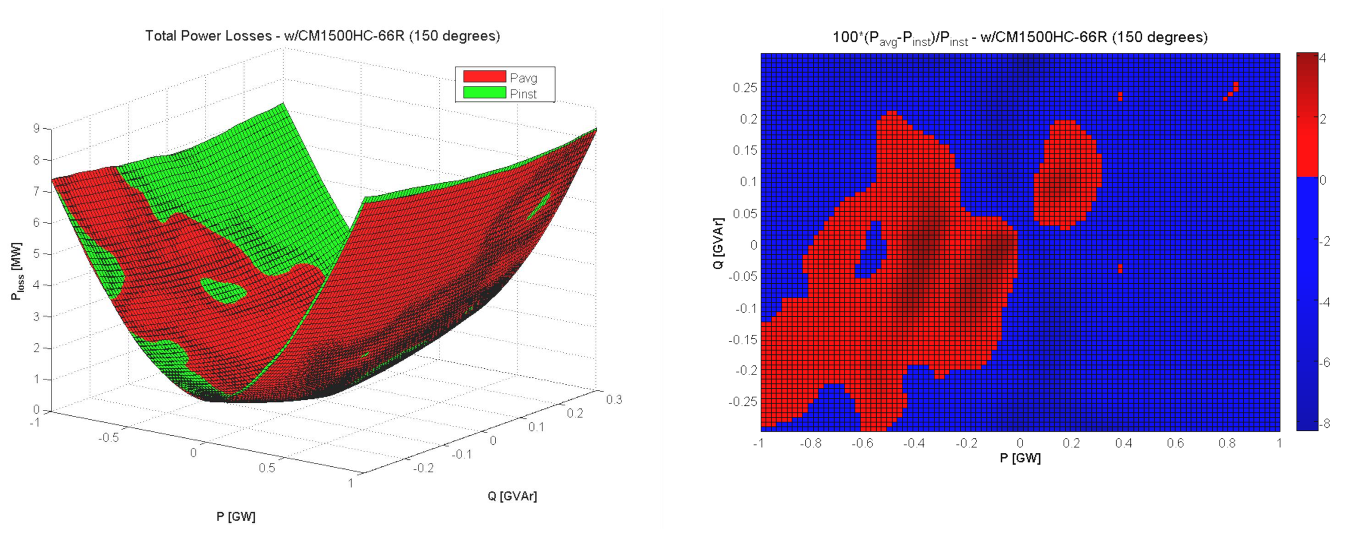
Simulation Losses Comparison Results

■ $p_{ACi} = \frac{P_{AC}}{3}$ ■ $p_{ACi} = \frac{P_{AC}}{3} + V_{gi} I_{gi} \cos(2\omega t + \varphi)$

Conduction losses: + Switching losses: + Passive elements losses:



= Total MMC losses:



Conclusion

- The impact of two control variants (compensation of the average or the instantaneous AC grid power) : differential and AC grid currents, capacitor voltages ripple, losses.

- compensation of the average AC grid power:
  - differential currents are constant
  - V_{ci_tot} ripple are 4% higher
- compensation of the instantaneous AC grid power:
  - differential currents have DC and AC components at 2ω
  - RMS differential currents is 11% higher
- Losses

Usual assumption is not every time validate

the MMC converter using considerable number of semiconductor; the losses are not only related to the RMS current value but also to the way of this current (diode or IGBT) → therefore to the control